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Energy savings potential of a novel radiative cooling and solar thermal collection concept in buildings for various world climates

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Abstract:

A novel radiative cooling and solar collection concept is presented, and the combination of these two technologies and its energy integration in residential and commercial buildings is evaluated. This innovative concept, herein named Radiative Collector and Emitter (RCE), allows for supplying both cooling and Domestic Hot Water (DHW) demands. First, the RCE concept is introduced by presenting its background, with special attention to the overlapping and switching between radiative cooling and solar thermal collection. Then the DHW and cooling demands for four building typologies, two residential and two commercial, are compared with the energy production of the RCE. The analysis is performed for representative cities of the world climates according to Köppen-Geiger classification. The RCE concept showed suitability in some of the studied cities (San Francisco, Cape Town, Johannesburg, London, and Ottawa) with C (temperate) and D (continental) climates in residential and tertiary buildings.

Introduction

Nowadays, the effect of fossil fuels on climate change has reached scientific consensus. New policies are focused on energy efficiency and on renewable sources to reduce the energy dependency on fossil fuels. In this sense, the building sector is one of the strategic sectors to achieve these new objectives. Residential and commercial buildings represent nearly 40% of total energy consumption in the European Union (EU-28) [1] (residential buildings 24.9% and commercial buildings 13.6% [2]). For instance, in the residential buildings energy budget, space conditioning of buildings represents 65% of it while Domestic Hot Water (DHW) 13.8 % [2].

For space conditioning purposes, active and passive strategies can be applied to reduce energy consumption. Despite these strategies, energy consumption cannot be usually reduced to zero if thermal comfort conditions are to be preserved [3]. It is at this point when renewable sources should emerge to cover these energy needs.

When talking about heating and DHW, solar thermal collectors are well known as an effective system to meet these heat demands [4]. However, for cooling there is still no simple renewable alternative with such potential and development as solar thermal collection is for heat demands. Two possibilities for cooling are compression heat pumps and absorption heat pumps. On the one hand, compression heat pumps are a non-renewable technology that needs substantial amounts of electricity, although according to some legislations they can be considered as renewable [5,6]. On the other hand, absorption heat pumps may use solar energy as driving heat, but they are not available for residential applications, have low overall efficiencies, require high operation temperatures, and need large cooling towers [7]. Moreover, their coupling with suitable solar heat sources is not well researched.

It is at that point where radiative cooling gains strength in providing cooling. This technology uses the sky as a heat sink taking advantage of its effective temperature lower than ambient. Thus, it may be a good option to supply the cooling demands of houses in hot and dry regions [8]. Lot of research has been conducted in the study of the radiative cooling phenomenon [9, 10] and, more recently, in the development of radiative cooling experimental prototypes and numerical/theoretical models. A comprehensive review of radiative cooling is presented in [11]. The research conducted in [12, 13] used unglazed solar collectors to test the radiative cooling achievable with a simple modification, showing the capability of cooling production. Recently, the research evolved into the development and testing of more sophisticated materials [14, 15] allowing the radiative cooling effect even under sunlight conditions, and achieving lower temperatures. Though, some other research has been conducted in the development and validation of a robust numerical model with experimental data [16]. However, despite the efforts done in this field, the few studied systems have not yet reached the market due to its low available cooling rates (between 20-80 W/m^2 [17], with peak values of 120 W/m^2 [18]). Therefore, new concepts and improvements are required for radiative cooling to become feasible.

Radiative cooling phenomenon is antagonist to solar thermal collection, mainly due to the different radiation wavelength used (longwave radiation for radiative cooling and shortwave radiation for solar thermal collection) and because solar thermal collection takes place during sunlight hours while radiative cooling mainly when there is no sunlight. A more detailed analysis of the differences between these two technologies is presented in [11].

Since both technologies can be conceived in analogous devices, it comes to mind to combine these technologies to provide heat and cold using a single device. However, these two technologies are not generally prepared to work together when they are designed to work autonomously [19]; therefore some adjustments have to be done for this purpose.

The combination of solar collection and radiative cooling in a single device would be a qualitative leap forward to renewable suitability for meeting different energy demands. The use of both technologies may substantially reduce the non-renewable

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primary energy consumption for space conditioning and domestic hot water. Moreover, the extra cooling savings for about the same economic investment will make the investment more cost-effective. This new concept that combines solar thermal collection and radiative cooling in a single device is based on radiation heat transfer, since it collects radiation (solar) from the Sun as a heat source, and emits radiation (thermal) to the sky to provide cooling. Therefore, this concept will be mentioned from here on as Radiative Collector and Emitter (RCE).

Up to now, little research has been conducted in this topic. Firsts attempts were focused in testing a device designed to perform one function (radiative cooling or solar collection) and see if the same device could also perform the other function. This research either used unglazed solar thermal collectors and observed radiative and convective cooling during the night [12, 20] or alternatively observed the production of heating during day by a radiative cooling device [21]. However, these systems were not designed to perform both functions and, thus, presented such low efficiencies that did not justify its usefulness. More recently, it was developed and tested a suitable material to be used for radiative cooling and solar heating [19]. Once the material was proved, it was built a prototype to be tested in real conditions, showing good performances [22]. However, these studies were limited to certain specific conditions, did not assess the potential of combining such technologies under different climatic conditions, and did not consider the heating and cooling demands.

Several energy and economic studies on the potential of a particular energy technology for the integration in different building types and various climates have been published recently. These technologies include solar absorption cooling [23], fuel cell micro-CHP [24] and building-integrated photovoltaics [25] as well as Smart-grid operation [26-27]. These studies show the interest of this type of methodologies and allow framing the present work, which is contributing with the above mentioned novel RCE technology to this type of building integration potential studies.

The purpose of this article is to introduce the RCE concept, which comprises two technologies: radiative cooling and solar collection, as well as to investigate and determine the RCE potential to cover cooling and DHW energy demands in residential and commercial buildings in different climates. For different climates, different building typologies were evaluated to determine the most suitable application. This worldwide climate suitability study has never been performed neither for radiative cooling nor for the novel RCE concept.

The RCE concept

The RCE concept presented in this paper is conceived as a device capable of producing heat and cold for any existing demand, in the present case for space conditioning and DHW demands. This concept produces heat and cold in the same manner as two separated devices would do. Similar devices already tested in the literature were designed to produce either heat or cold and, without any modification of the original device, the other service was studied [11, 20, 21]. The RCE concept is conceived since the beginning to produce both. This commitment entails the use of some strategies in the design of it to allow the generation of such different energy products.

The RCE device was conceived to have a similar architecture to a flat plate solar thermal collector, namely, it has an absorber/emitter surface and a cover on top of it. Additionally to that, it was also conceived to be capable of working in two modes: solar collection mode and radiative cooling mode (Figure 1a), producing both heat and cold. To be able to operate under these different modes, the RCE incorporates a movable cover (Figure 1b). This cover is composed of two different sections (one for each operation mode) made of different materials. The main drawback of this system is the movable element in the cover that did not exist before, therefore presenting a potential increase in maintenance needs.

The section of the cover used for the solar collection mode lets solar radiation pass through and blocks mid and far infrared radiation. On the contrary, the section used for radiative cooling lets thermal radiation pass through. The two different sections of the cover are exchanged for each operation mode via a sliding cover system. The absorber/emitter surface is assumed to have blackbody properties. These considerations were taken into account when evaluating the energy production of the RCE device.

The operation and control of the two sections of the cover should be done considering both the presence of solar radiation and the time of the day. When there is solar radiation the device is operated in the solar collection mode; on the other hand, when there is no solar radiation and the time is between dusk and dawn the device is operated in the radiative cooling mode.

The RCE device needs to be connected with the HVAC and DHW installation (cold and hot tanks) of the building, providing such systems with heat and cold. In terms of HVAC, any distribution system can be used to deliver the cold to the different spaces to condition. Thus, systems such as radiant ceilings that require lower temperature differences between the circulating water and the ambient set-point can be used. These systems could provide better thermal comfort [28-29] but also need additional systems to cope with the latent heat. The distribution system is not the goal of this research and it is therefore not considered in the analysis.

Methods

To evaluate the coverage of the cooling and DHW demands by the RCE under different climatic conditions, the energy production of the RCE and the energy demand of the different building typologies were determined as shown in this section (Figure 1a).

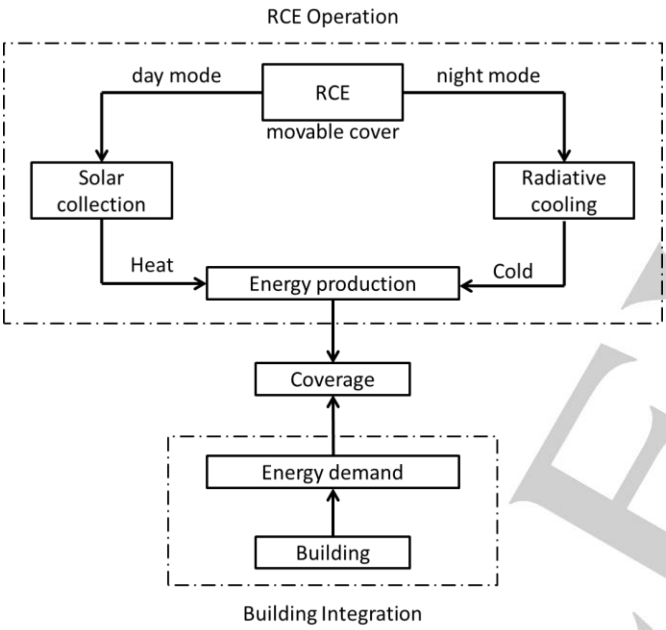
Energy production

The RCE total energy production was calculated for each mode separately (Figure 1a) having each mode its own calculations and procedures. However, some considerations are made for both modes.

A steady-state model is developed to determine the energy production potential under different climates, thus helping to identify and highlight most interesting applications and world climates for such new technology.

Conductive and convective losses are assumed to be negligible in the RCE device, since the RCE is considered to incorporate strong thermal insulation and an evacuated space between the absorber/emitter surface and the cover.

The tilt angle, which is a relevant parameter for the RCE, is selected to achieve the best results under radiative cooling operation, because this is the technology with lower production rate. Since the best tilt angle for radiative cooling is horizontal [30], the RCE is considered to have an inclination angle of 0º. This may result in a decrease of the solar collection efficiency since the angle is not optimum for solar collection.



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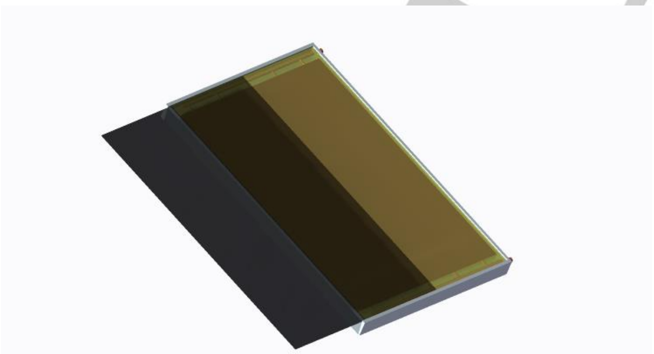


b

Figure 1. a) Block diagram for Radiative Collector and Emitter concept and its building integration. b) 3D representation of a Radiative Collector end Emitter device.

The optical properties of the different covers used are (Table 1): for the solar collection mode perfect transmission in the solar spectrum and blocking of thermal radiation (similar to glass), for the radiative cooling mode perfect transmission in the whole spectrum (similar to low-density polyethylene). These optical properties are not the exact ones of real materials (for instance glass or polyethylene). However, the aim of this paper is to assess the potential of such technology, therefore the assumption of such values is considered to be valid.

Table 1. Optical properties of the cover for each operation mode.

	Transmissivity in the solar spectrum	Transmissivity in the thermal spectrum
Solar collection mode	1	0
Radiative cooling mode	1	1

Solar thermal collector mode

For solar collection the RCE energy production potential was evaluated considering the Global Horizontal Irradiance (GHI) and a system performance ratio (Eq. 1). The system performance ratio is a common methodology used in other research [31] and takes into account in a single parameter all the inefficiencies of the system (solar collector efficiency, losses due to inclination and shadows, etc.). Based on previous works [31], a similar performance ratio of 0.6 was used for the solar collection calculations.

$$P_{solar,net}\left[\frac{W}{m^2}\right] = GHI \cdot \eta_{sc} \qquad \text{Eq. 1}$$

The energy production was monthly evaluated to be compared to the DHW demands (Eq. 2).

$$E_{solar,month}\left[\frac{Wh}{m^2 \cdot month}\right] = \sum\nolimits_{month} P_{solar,net} \cdot \Delta t \qquad \text{Eq. 2}$$

Radiative cooling mode

Radiative cooling potential has not been widely studied [32] and there are no world potential maps available. Therefore, some assumptions were considered to standardize the results and to present its potential in a similar way as solar thermal collection.

Apart from the assumptions already presented for the RCE concept, the absorber/emitter surface temperature also needs to be considered. The surface is assumed to be at a constant temperature of 20°C for the periods where cooling is required. This absorber average surface temperature along the night is considered a good trade-off between an acceptable upper limit for achieving internal fluid temperatures low enough to be used in HVAC systems, and a reasonable lower limit for good radiative cooling performances.

Given these assumptions, the radiation balance between the sky and the radiator is presented in Eq. 3. The monthly energy production was determined considering only the time when there is no solar radiation (Eq. 4). The clear sky emissivity was calculated using empirical correlations (Eq. 5, Eq. 6, Eq. 7) bearing in mind the climate for which they were proposed [33-35] (Table 3). The opaque fraction of the sky was also considered to evaluate the effective sky emissivity. In that sense, Eq. 8 was used to modify the clear sky emissivity based on empirical correlations [36] and data from EnergyPlus weather data.

$$P_{radiator,net}\left[\frac{W}{m^2}\right] = \varepsilon_{radiator} \cdot \sigma \cdot T_{radiator}^4 - \varepsilon_{sky} \cdot \sigma \cdot T_{ambient}^4 \quad \text{Eq. 3}$$

$$E_{radiator,month}\left[\frac{Wh}{m^2 \cdot month}\right] = \sum_{month} P_{radiator,net} \cdot \Delta t \quad \text{Eq. 4}$$

Empirical correlations for clear sky emissivity:

$$\varepsilon_{sky,0} = 0.711 + 0.56 \cdot \left(\frac{T_{dp}}{100}\right) + 0.73 \cdot \left(\frac{T_{dp}}{100}\right)^2 \quad \text{Eq. 5}$$

$$\varepsilon_{sky,0} = 0.741 + 0.0062 \cdot T_{dp} \quad \text{Eq. 6}$$

$$\varepsilon_{sky,0} = 0.754 + 0.0044 \cdot T_{dp} \quad \text{Eq. 7}$$

Effective sky emissivity:

$$\varepsilon_{sky} = clf + (1 - clf) \cdot \varepsilon_{sky,0} \quad \text{Eq. 8}$$

Energy demands

The DHW and cooling demands of the different buildings considered were determined by numerical simulation using EnergyPlus for the same locations where the energy production was calculated. To standardize the results, four typologies of standard buildings were chosen. These buildings were taken from the USA Department of Energy (DOE), which provides a set of prototype building models to be used in EnergyPlus. These models are either based on the International Energy Conservation Code (IECC) for residential buildings [37] or the ASHRAE Standard 90.1 for commercial buildings [38].
For the present work 2 residential and 2 commercial buildings were chosen to represent a large share of the existing building stock. These 4 buildings are: a single-family (SF) detached house with crawlspace (Figure 2a), a multi-family (MF) low-rise apartment building with crawlspace (Figure 2b), a medium office (Figure 2c), and a small hotel (Figure 2d). The main geometric parameters describing the selected building typologies are presented in Table 2.

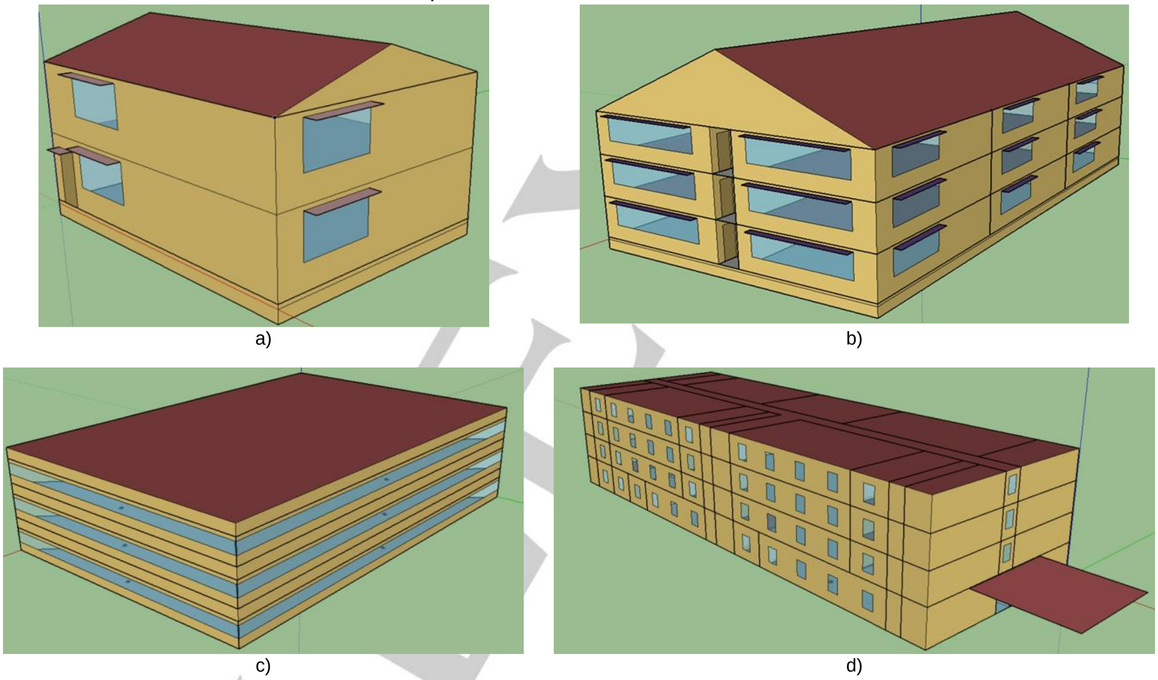


Figure 2. Analysed buildings: a) Single-family detached house; b) Multi-family low-rise apartment building; c) Medium office; d) Small hotel.

Table 2. Geometric parameters of the different buildings analysed and additional passive and active strategies.

	SF building	MF building	Office	Hotel
Wall area (m^2)	221.2	876.2	1978.0	1694.2
Window area (m^2)	33.2	246.9	652.6	184.2
Window-Wall Ratio [%]	15%	28%	33%	11%
Net Conditioned Area (m^2)	223.1	2007.4	4982.2	4013.6
Roof Area (m^2)	116.4	784.9	1660.5	1003.4

Additional passive and active strategies				
Cooling set point temperature (°C)	25	25	25/27 (schedule)	25
Summer night ventilation	20-8h	20-8h	-	-
Natural ventilation through occupants controlled windows	-	-	7-22 h	-
Solar protection (Overhangs)	Included	Included	-	-

These standard buildings are fully defined in terms of envelope, schedules, internal loads, DHW consumption, etc. [37, 39]. Nevertheless, some additional active and passive strategies not considered by the original models were included to make the models closer to the real behavior and also more efficient (set point temperature schedules, summer night ventilation, overhangs, etc. see Table 2).

For each climate, some of the building characteristics of the standardized models, such as the overall heat transfer coefficient (U-factor) of the building envelope elements (roofs, walls, floors, doors, windows), and the solar heat gain coefficient (SHGC) of the non-opaque envelope elements (windows), change according to the previously mentioned codes (IECC/ASHRAE Standard 90.1). As these codes are ASHRAE standards, the building models are also referred to ASHRAE climate zones. However, in this paper a worldwide climate analysis using the Köppen-Geiger climate classification [39] is performed, since it is a more general and known climate classification. For this purpose, the model used for a particular climate of the Köppen-Geiger classification was chosen according to its similarity to the ASHRAE climate zone (Table 3).

Table 3. Representative cities, sky emissivity correlation used and equivalences between Köppen-Geiger classification, USA climate and IECC.

<table>
<tr><th rowspan="2">Representative Cities</th><th colspan="2">Sky emissivity correlation</th><th rowspan="2">Köppen-Geiger classification[a]</th><th rowspan="2">ASHRAE climate zone</th><th rowspan="2">IECC climate zone model used</th></tr>
<tr><th>Clear</th><th>Cloudy</th></tr>
<tr><td>Singapore, Caracas</td><td>Eq. 5</td><td rowspan="8">Eq. 8</td><td>Af/Am[b]/Aw</td><td>1A</td><td>1</td></tr>
<tr><td>Riyadh</td><td>Eq. 7</td><td>BWh/BSh[b]</td><td>1B/2B</td><td>2</td></tr>
<tr><td>Denver, Teheran</td><td>Eq. 7</td><td>BWk[b]/BSk</td><td>3B/4B/5B</td><td>3</td></tr>
<tr><td>Rome, Perth, San Francisco, Cape Town</td><td>Eq. 5</td><td>Csa/Csb</td><td>2A/3C</td><td>2</td></tr>
<tr><td>Brisbane, Tokyo, Johannesburg</td><td>Eq. 5</td><td>Cfa/Cwa[b]/Cwb</td><td>2A/3A/4A</td><td>3</td></tr>
<tr><td>London</td><td>Eq. 5</td><td>Cwc[c]/Cfb/Cfc[c]</td><td>4C/5C</td><td>5</td></tr>
<tr><td>Pyongyang, Chicago</td><td>Eq. 6</td><td>Dsa[b]/Dwa/Dfa</td><td>5A</td><td>5</td></tr>
<tr><td>Ottawa</td><td>Eq. 6</td><td>Dsb[b]/Dwb[b]/Dfb</td><td>6A/6B/7A/7B</td><td>6</td></tr>
<tr><td>-</td><td colspan="2">-</td><td>Dsc[c]/Dsd[c]/Dwc[c] Dwd[c]/Dfc[c]/Dfd[c] ET[c]/EF[c]</td><td>7A/7B/8</td><td>7</td></tr>
</table>

[a] Köppen-Geiger climate classification [39]
[b] Climate not considered or climatic data from a representative city not found.
[c] Climate not considered, cold climate or without cooling requirements.

In the present paper 16 representative cities were studied covering most of the climates of Köppen-Geiger climate classification (Table 3). For some climates two cities were selected since the differences between them were sufficiently significant to consider more than one city. Climates that do not require cooling demands were not considered in this study, since the technology under study aims at providing both DHW and cooling. Once the climates and the building models were chosen, the energy demands were calculated. Although the time step for the building simulations was of 15 min, only monthly demands were considered for coverage purposes.

Coverage calculations

Once the demand and the production were calculated, the percentage of coverage was also evaluated. The coverage is an important parameter since it can represent the suitability of this technology for a particular combination of climate and building typology. In other words, it means how well the energy production from the new RCE concept can match the energy demands of the building in that specific climate. In any case, the production of renewable heating and cooling with the RCE can contribute to significant energy and money savings, even if its contribution to the total building HVAC demand is small.

The energy coverage was determined as the minimum between the monthly energy demand and the monthly energy production. The heat and cold produced is only used to cover the DHW and the cooling demands. When there is an excess of energy production it is not used.

Since for different cities both the energy demand and production change the coverage for a fixed surface of RCE changes as well. Therefore, a parametric analysis of the DHW coverage was performed to show how changing the surface affects the coverage of the energy requirements.

Results and Discussion

Simulations to calculate the energy demand (DHW and cooling) of different building typologies and the energy production of RCE were performed in 16 cities. The aim of these simulations was to evaluate the RCE suitability in each city and, consequently, each climate. The results to assess that suitability are presented and discussed in this section.

The annual results of all cities for every building typology are shown in Figure 3. This figure includes the energy demand, the energy production and the percentage of coverage per square meter of conditioned surface considering an installed RCE surface of: 5 m^2 for the single-family house, 30 m^2 for the multi-family house, 20 m^2 for the office and 100 m^2 for the hotel. These surfaces were chosen according to the DHW demand, trying to cover a significant part of it, and also considering that there was enough room on the roof of these buildings (the percentage of covered roof was in the range of 2-6%).

In Figure 3 it is observed that with an installed surface of 5 m² much of the DHW energy demand of a single-family house can be covered in most of the cities. Also, cooling demands are partially covered. The multi-family building is behaving similarly to the single-family house. In contrast, the office seems to be the most different building typology when evaluating its demands. Its cooling demands are much higher than the DHW ones. This is mainly due to the higher internal loads and the higher requirements of air ventilation in the office. Moreover, the DHW demand of the office is low, and can be covered with 20 m² of RCE. Finally, the hotel typology has a higher DHW demand than the office. This high DHW demand requires a large amount of RCE installed surface (100 m²) to have reasonable coverage, leading to higher cooling coverage than the office. On the other hand, the cooling energy demand is also higher than in the office since the use of natural ventilation in this building typology is not considered.

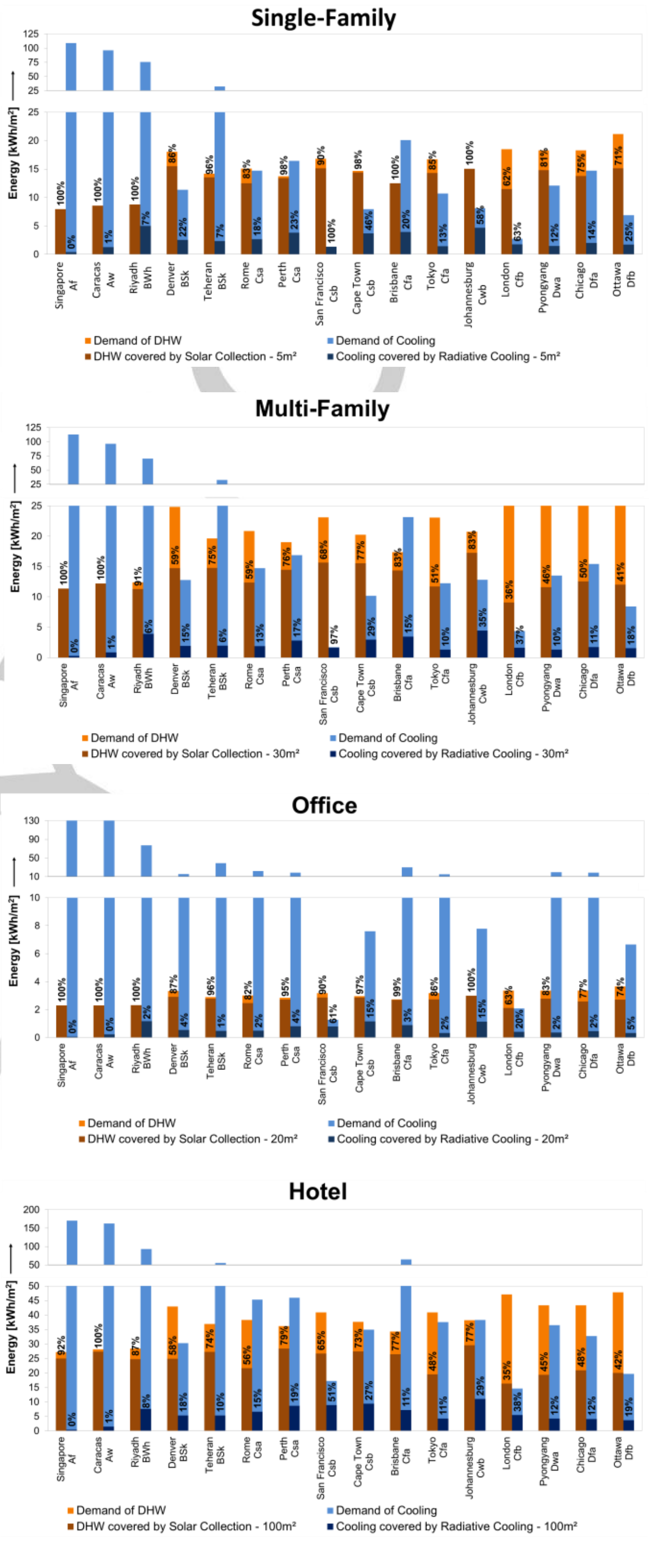


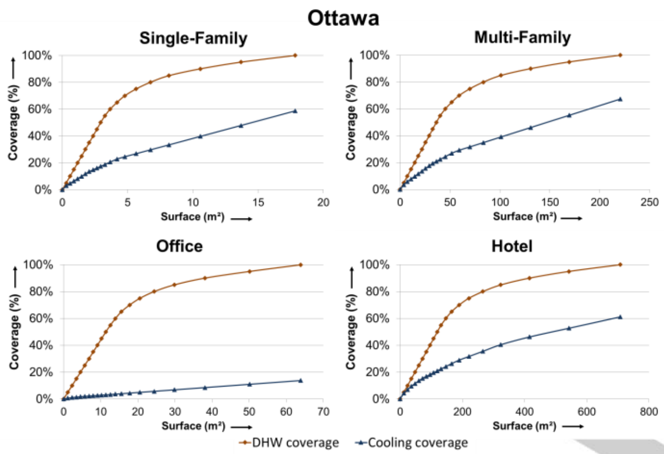
Figure 3. Annual energy demand, production and percentage of coverage for 16 cities and per square meter of conditioned surface considering an installed surface of Radiative Collector and Emitter of: 5 m^2 for the single-family house; 30 m^2 for the multi-family house; 20 m^2 for the office; 100 m^2 for the hotel.

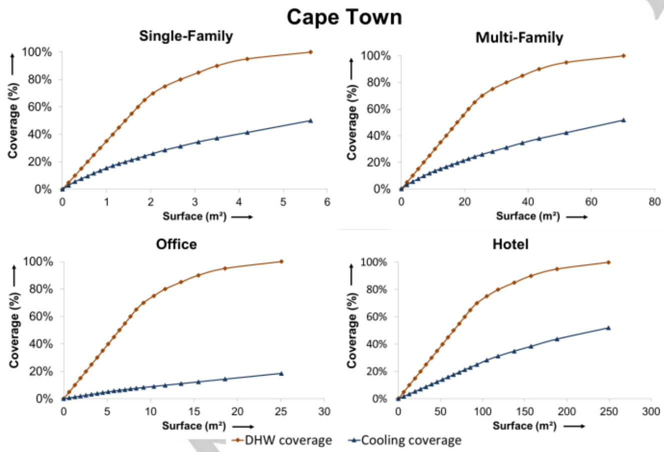
Analyzing the different building typologies, one can see that for residential buildings the cities with low cooling demands match better with the new RCE concept. Other cities require a lot more RCE installed surface to cover a significant part of the cooling demand.

The office is the less suitable building typology due to its high cooling demand combined with low DHW demand. This scenario requires using the RCE mainly in radiative cooling operation mode, and thus not taking benefit of its use in solar thermal collector operation mode.

Finally, the hotel is an intermediate case between residential buildings and the office because of its high DHW demand. However, for the warmest cities it may be better using the RCE mainly in the radiative cooling operation mode and reducing its use as solar thermal collection to avoid excess heat.

A parametric analysis of the DHW coverage was performed to observe how the different energy coverages change with the installed surface. For the sake of clarity just 3 cities (Ottawa, Cape Town and Teheran) are shown, according to different weather conditions (cold, mild and warm) (Figure 4).





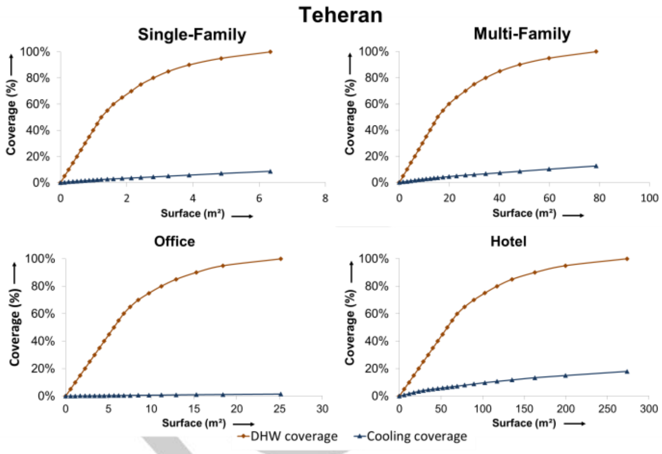


Figure 4. Parametric analysis of Domestic Hot Water and cooling coverage against installed Radiative Collector and Emitter surface for building typology in Ottawa (top), Cap Town (middle) and Teheran (bottom).

A constant relation between DHW coverage and installed surface is observed in Figure 4. There is a turning point beyond which the required surface increases drastically. Therefore, the optimal coverage is close to this point which is located approximately between 50-75% of DHW coverage. This optimal point agrees with some policies of minimum solar coverage of DHW demand in some countries [40]. Based on this result, the cooling energy savings when an installed surface of RCE covers at least the 75% of DHW demand are presented for all 16 initial studied cities. An indivisible RCE unit of 2 m^2 of surface is considered. A world map for each building typology with the cooling savings is shown in Figure 5 with the corresponding data presented in Table 4.

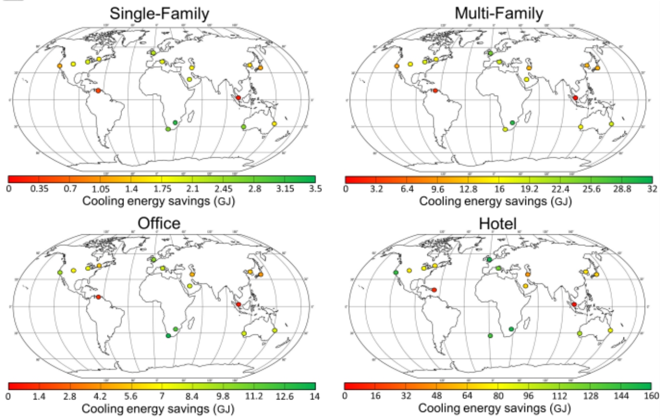


Figure 5. Cooling savings for an installed Radiative Collector and Emitter surface to cover a minimum of 75% of Domestic Hot Water demand for the studied locations (based on Radiative Collector and Emitter units of 2 m^2 of surface).

From the results shown in Figure 4 and 5 and presented in Table 4, it is observed that there exists a significant potential for RCE technology to cover the DHW and cooling demands.

Therefore, to determine the cities and building typologies with higher potential for RCE implementation, a common criteria was defined (Table 5). The present study aimed at getting the maximum benefit of the RCE concept, thus using it both as solar thermal collector and radiative cooling. Therefore, a minimum DWH coverage of 75% and a minimum cooling coverage of 25% were defined as common criteria. Other climates or cities may also be suitable for RCE implementation although they may get benefits mainly from either solar thermal collection or radiative cooling, but not both.

Table 5 presents the different cities meeting the criteria, as well as the climate zone where they belong. The results evidence a significant difference between residential and commercial buildings, especially the office which is the most different building typology. Residential buildings show more suitability due to the more balanced demand between heat and cold. Hotel typology presents a similar behavior to residential buildings. On the other hand, office buildings show suitability in relatively cold climates, where cooling demands are low.

Table 4. Domestic Hot Water /Cooling coverage and savings for an installed Radiative Collector and Emitter surface covering a minimum of 75% of Domestic Hot Water demand for the studied locations (based on Radiative Collector and Emitter units of 2 m^2 of surface)

	Single-Family			Multi-Family			Office			Hotel		
	Surface(m²)	DHW savings (GJ) and coverage (%)	Cooling savings (GJ) and coverage (%)	Surface(m²)	DHW savings (GJ) and coverage (%)	Cooling savings (GJ) and coverage (%)	Surface(m²)	DHW savings (GJ) and coverage (%)	Cooling savings (GJ) and coverage (%)	Surface(m²)	DHW savings (GJ) and coverage (%)	Cooling savings (GJ) and coverage (%)
Singapore	2	6.36	0.12	18	64.99	1.11	10	36.24	0.62	82	296.04	5.06
		100%	0%		79%	0%		88%	0%		75%	0%
Caracas	2	6.86	0.41	16	68.21	3.30	8	34.24	1.65	72	306.96	14.84
		99%	1%		77%	0%		83%	0%		75%	1%
Riyadh	2	5.91	1.91	20	68.06	17.84	8	33.34	8.78	74	309.62	81.12
		84%	3%		76%	4%		80%	1%		75%	6%
Denver	4	11.40	1.65	46	135.98	19.78	14	40.52	6.96	150	467.28	96.73
		79%	18%		76%	21%		75%	2%		75%	22%
Teheran	4	10.32	1.55	30	106.56	14.60	10	39.48	4.74	104	401.93	79.28
		91%	6%		75%	6%		76%	1%		76%	10%
Rome	4	9.18	1.74	50	114.55	22.13	16	40.52	6.96	168	415.86	132.82
		76%	15%		76%	21%		75%	2%		75%	20%
Perth	4	10.17	2.49	30	104.52	20.12	12	40.83	8.83	94	395.66	117.22
		92%	19%		76%	17%		80%	3%		76%	18%
San Francisco	4	11.40	1.07	38	126.97	12.30	14	45.15	10.08	128	445.23	148.20
		84%	100%		76%	100%		79%	44%		75%	60%
Cape Town	4	11.03	2.57	30	112.21	21.37	12	42.91	13.76	106	409.68	143.82
		88%	32%		77%	29%		81%	10%		75%	29%
Brisbane	2	7.55	1.51	26	97.06	21.92	10	37.77	8.81	96	372.13	99.85
		75%	9%		77%	13%		77%	2%		75%	11%
Tokyo	4	12.78	1.54	48	125.98	13.87	16	43.54	4.69	164	445.57	80.47
		95%	18%		76%	16%		76%	2%		75%	15%
Johannesburg	4	11.60	2.43	28	118.65	30.45	10	42.41	12.12	98	417.82	156.04
		96%	37%		79%	33%		79%	9%		76%	28%

London	10	11.81	1.94	106	137.94	26.55	34	45.74	10.63	350	510.95	157.65
		80%	88%		75%	84%		76%	28%		75%	75%
Pyongyang	6	13.19	1.60	54	138.45	14.25	18	47.60	6.02	174	472.06	87.63
		90%	16%		76%	15%		79%	2%		75%	17%
Chicago	6	12.27	1.99	62	137.14	21.43	20	46.30	8.28	198	468.97	97.90
		84%	17%		75%	19%		77%	2%		75%	21%
Ottawa	6	13.53	1.53	70	157.30	19.35	22	50.31	6.23	222	519.11	90.27
		80%	28%		75%	32%		77%	5%		75%	32%

Table 5. Criteria values and suitable cities and climates.

	Single-Family	Multi-Family	Office	Hotel
Min. Cooling coverage	25%			
Min. DHW coverage	75%			
Cities accomplishing criteria values	San Francisco, Cape Town, Johannesburg, London, Ottawa	San Francisco, Cape Town, Johannesburg, London, Ottawa	San Francisco, London	San Francisco, Cape Town, Johannesburg, London, Ottawa
Climates of suitable cities (Köppen-Geiger classification)	Csb, Cwb, Cfb, Dfb	Csb, Cwb, Cfb, Dfb	Csb, Cfb	Csb, Cwb, Cfb, Dfb

The cities presenting most potential in terms of demand coverage are presented in Table 5. Although the extrapolation from cities to climates is not direct, the cities located in climates presented in Table 5 may present a higher potential in terms of demand coverage than the other ones. However, other locations may also present important absolute energy savings with low demand coverages. As an example, the results from Cape Town and San Francisco can better explain the debate. A single-family house in San Francisco presents high cooling demand coverage (100%), whereas in Cape Town it presents a lower coverage (32%). However, Cape Town produces much more cooling energy savings (2.57 GJ vs 1.07 GJ) when both have the same RCE installed surfaces.

Conclusions

In the present work the building integration potential of a new concept, the Radiative Collector and Emitter (RCE), was presented. To determine the heat and cold production a simplified model was used.

The results showed that in several cities located in different Köppen-Geiger climate classification regions the use of the RCE concept in residential and commercial buildings is suitable, and the building demand will take advantage from the combined capacity of the RCE to produce both heat and cold. For the Single-Family, Multi-Family, and Hotel building typologies, a minimum coverage of 25% of cooling and 75% of DHW is achieved in five of the studied cities (San Francisco, Cape Town, Johannesburg, London, and Ottawa), representing four climate zones (Csb, Cwb, Cfb, Dfb). On the other hand, the Office building typology achieves these levels of coverage in only two of the studied cities (San Francisco and London), representing two climate zones (Csb, Cfb).

Other studied cities showed less benefit from the use of RCE, since either heat or cold were the major demand. The conditions were not suitable to make use of the combined capacity to produce heat and cold because mainly one demand was required.

Therefore, to take full advantage of the RCE concept, an appropriate ratio between cooling and DHW demand is required. This ratio depends on the climate but also on the building typology. Some climates are not adequate because they are either too hot or too cold to meet both requirements. Therefore, only one technology (radiative cooling for hot climates or solar thermal collection for cold climates) is mainly required, being the other less needed or unnecessary. Regarding building typologies, those with a constant demand of heat during the whole year, such as DHW, make RCE more suitable, since both heat and cold production can be used.

The potential presented in this paper outlined a first approach to determine in which combinations of climates and building typologies this novel RCE concept may be implemented. However, further research should be done in the development of a more detailed numerical model of the RCE concept. This model could then be used for economic viability studies in certain locations.

Nomenclature

Symbol	Description
clf	Opaque fraction of the sky[-]
$E_{radiator,month}$	Monthly radiative cooling energy $\left[\frac{Wh}{m^2 \cdot month}\right]$
$E_{solar,month}$	Monthly solar thermal collection energy $\left[\frac{Wh}{m^2 \cdot month}\right]$
GHI	Hourly average global horizontal irradiation $\left[\frac{W}{m^2}\right]$
$P_{solar,net}$	Hourly average solar radiation power $\left[\frac{W}{m^2}\right]$
$P_{radiator,net}$	Hourly average radiative cooling power $\left[\frac{W}{m^2}\right]$
$T_{ambient}$	Ambient temperature [ºC]
$T_{radiator}$	Temperature of the radiator surface [ºC]
T_{dp}	Dew point temperature [ºC].
Δt	Time step [h]
$\varepsilon_{radiator}$	Emissivity of the radiator (ideally $\varepsilon_{radiator}$ = 1) [-]

ε_{sky}	Effective sky emissivity [-]
$\varepsilon_{sky,0}$	Sky emissivity under clear sky conditions [-]
η_{sc}	solar collector performance ratio [-]
σ	Stefan-Boltzmann constant $\left[\frac{W}{m^2 \cdot K^4}\right]$

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Keywords: Radiative cooling • Solar thermal collection • Renewable energy • Low grade energy source • Building integration

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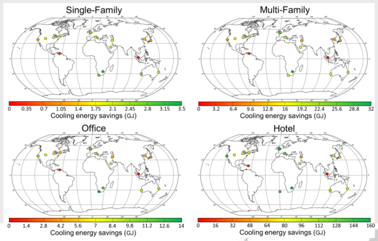

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